

APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

ASYMMETRY CORRECTION FOR MAGNETO-RESISTIVE HEADS

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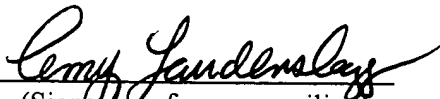
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ASYMMETRY CORRECTION FOR MAGNETO-RESISTIVE HEADS

BACKGROUND OF THE INVENTION

Field of the Invention

5 The present invention relates to magnetic disk drives and, more specifically, to signal processing circuits for magneto-resistive (MR) heads.

Description of the Related Art

10 The principle of operation of MR heads is based on the ability of metals to change their resistance in the presence of a magnetic field. A typical MR head has an MR element composed of a thin film (e.g., about 250 nm in thickness) of Ni-Fe alloy, also called permalloy, which converts magnetic field variations at the surface of a magnetic storage medium (e.g., a magnetic platter) into resistance variations. The resistance variations are then converted into a differential voltage swing at the output of the MR head.

15 MR technology solves numerous problems associated with magneto-inductive heads, such as the dependence of signal amplitude on the rotational speed of the magnetic disk. However, MR heads have created new challenges for disk drive designers. One problem is the asymmetry in the response of a biased MR element to magnetic flux changes of opposite polarity. As a result, positive and negative pulses in the output signal of the MR head have different amplitudes, which impairs both servo and read channel performance in the disk drive.

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SUMMARY OF THE INVENTION

 Problems in the prior art are addressed, in accordance with the principles of the present invention, by an asymmetry-reducing circuit adapted to process an input signal having positive and negative pulses of different amplitudes and generate a corresponding balanced signal having positive and negative pulses of substantially uniform amplitudes. The asymmetry-reducing circuit balances the input signal by providing signal contributions corresponding to the second and third orders of the input signal. In a representative embodiment, the asymmetry-reducing circuit includes a differential amplifier and a plurality of arrayed MOS transistors connected to its inputs and outputs such that source-to-drain conductance of the transistors provides input and feedback resistances to the amplifier. A switch set selectively couples the fingers (gates) of the transistors to the input signal to modulate the source-to-drain conductance with said signal such that the input and feedback resistances change in a complementary manner. Advantageously, circuits of the invention can correct signal asymmetry within a relatively wide asymmetry range.

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BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and benefits of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

Fig. 1 shows a block diagram of an exemplary disk drive, in which the present invention can be practiced;

Fig. 2 shows a block diagram of a read/write channel that can be used in the disk drive shown in Fig. 1;

Fig. 3 shows a block diagram of a prior-art magneto-resistive asymmetry (MRA)-correcting circuit that can be used in the read/write channel shown in Fig. 2;

Fig. 4 shows a block diagram of an MRA circuit that can be used in the read/write channel shown in Fig. 2 according to one embodiment of the present invention;

Fig. 5 shows a block diagram of an MRA circuit that can be used in the read/write channel shown in Fig. 2 according to another embodiment of the present invention;

Fig. 6 shows a block diagram of an MRA circuit that can be used in the read/write channel shown in Fig. 2 according to yet another embodiment of the present invention;

Fig. 7 shows a diagram of a circuit having four MOS devices that can be used in the MRA circuit shown in Fig. 6 according to one embodiment of the present invention; and

Figs. 8A-B show diagrams of two circuits that can be used in the switch sets of the MRA circuit shown in Fig. 6 according to one embodiment of the present invention.

DETAILED DESCRIPTION

Reference herein to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

Fig. 1 shows a block diagram of an exemplary disk drive **100**, in which the present invention can be practiced. Disk drive **100** is coupled to a host device, e.g., a computer, and includes one or more magnetic platters **102** mounted on a spindle motor (not shown), one or more read/write heads **104** mounted on an actuator assembly **124**, amplifiers **106**, a read/write channel **108**, and a controller **110**. Read/write channel **108** is coupled via interfaces **114** and **116** to amplifiers **106** and via interfaces **118** and **120** to controller **110**. For clarity, certain components of disk drive **100**, e.g., the servo/actuator motor control, are not shown in Fig. 1.

To read from disk drive **100**, the host device provides to controller **110** a location identifier for the data to be retrieved. Based on the location identifier, controller **110** determines the actual physical location, e.g., the cylinder and sector, corresponding to the data on platters **102**. Controller **110** then generates an appropriate control signal for actuator assembly **124** to position read/write heads **104** such that they can access that physical location. With read/write heads **104** in the proper position, platters **102** are spun under the heads, which causes each head to generate an analog signal corresponding to the magnetic flux reversals representing data on the platters. The analog signal is then amplified in amplifiers **106** and applied via interface **114** to read/write channel **108**. As will be discussed in more detail below, read/write channel **108** decodes the amplified signal and converts it into a digital binary signal that is passed via interface **118** to controller **110**. Controller **110** may apply additional processing, e.g., caching and error detection/correction, to the data carried by the binary signal before providing the data to the host device. The additional processing is usually intended to increase the operating speed and/or reliability of disk drive **100**.

To write to disk drive **100**, the host device provides to controller **110** data to be stored along with a location identifier to be used. Based on the location identifier, controller **110** generates an appropriate control signal for actuator assembly **124** to properly position read/write heads **104**. Controller **110** then sends the data via interface **120** to read/write channel **108**. Read/write channel **108** encodes the data and generates an appropriate analog signal that is applied via interface **116** and amplifiers **106** to read/write heads **104**. With read/write heads **104** in the proper position, platters **102** are spun under the heads, which causes each head to impart magnetic flux reversals corresponding to the data onto the platters.

Fig. 2 shows a block diagram of a read/write channel **208** that can be used as read/write channel **108** in disk drive **100**. Read/write channel **208** has a read path **220** and a write path **250**. During a read operation, read path **220** converts analog signals received from the MR heads via interface **114** into the corresponding binary digital data that are output from read/write channel **208** via interface **118**. Similarly, during a write operation, write path **250** converts binary digital data received from the host device via interface **120** into the corresponding analog signals that are output from read/write channel **208** via interface **116** and used to impart magnetic flux reversals onto magnetic platters. Read/write channel **208** also has a clock synthesizer **270** adapted to generate clock signals for the read and write paths. In one embodiment, read/write channel **208** is adapted to support Partial Response Maximum Likelihood (PRML) coding and is implemented in an integrated circuit manufactured using a complementary metal oxide semiconductor (CMOS) process.

Write path **250** includes a parallel-to-serial converter **252**, a run-length-limited (RLL) encoder **254**, a parity encoder **256**, a write pre-compensation circuit **258**, and a driver circuit **260**. Parallel-to-serial converter **252** receives a parallel stream of data, e.g., eight bits per clock cycle, via interface **120**, converts

the parallel stream into a serial stream, and sends the serial stream to RLL encoder **254**. RLL encoder **254** encodes the serial stream into symbolic binary sequences according to a known RLL algorithm. An exemplary RLL algorithm uses a 32/33-bit symbol code designed to ensure that flux reversals on the magnetic platter are optimally spaced and that long runs of data without flux reversals are avoided. The RLL-encoded data are then passed to parity encoder **256** configured to add parity bits to the data and convert the parity-encoded data into a corresponding analog signal. The analog signal is then applied to write pre-compensation circuit **258**, which dynamically adjusts pulse widths/amplitudes in the analog signal to pre-compensate for signal distortions produced during the recording process. The adjusted analog signal is passed to driver circuit **260**, which drives the read/write heads via interface **116**. In one embodiment, driver circuit **260** is a pseudo emitter-coupled logic (PECL) driver circuit adapted to generate a differential output signal.

Read path **220** includes an attenuation circuit (input resistance) **222**, a variable-gain amplifier (VGA) **224**, a magneto-resistive asymmetry (MRA)-correcting circuit **226**, a continuous time filter (CTF) **228**, a buffer **230**, an analog-to-digital converter (ADC) **232**, a finite impulse response (FIR) filter **234**, an interpolated timing recovery (ITR) circuit **236**, a Viterbi detector **238**, a parity decoder **240**, and a run-length-limited (RLL) decoder **242**. An amplified signal received via interface **114** from the read/write head is first passed through circuit **222** serving signal attenuation and impedance matching purposes. The output of circuit **222** is then coupled to VGA **224** configured to adjust the signal amplitude for further signal processing. The adjusted signal is applied to MRA circuit **226** designed to reduce signal imbalance present due to the magneto-resistive asymmetry effects in the read/write head. More details on the principles of operation and structure of MRA circuit **226** are given below.

The output of MRA circuit **226** is applied to CTF **228** to attenuate high-frequency noise and minimize aliasing into the baseband after sampling. ADC **232** receives, via buffer **230**, the signal filtered by CTF **228**, samples it, and converts it into a digital form. The digital signal is passed to FIR filter **234** (e.g., a 10-tap FIR filter) and timing recovery circuit **236**. Timing recovery circuit **236** is connected in a feedback arrangement (not shown in Fig. 2) to FIR filter **234**, MRA circuit **226**, and VGA **224** to provide appropriate timing correction based on the frequency of the signal being processed. The digital signal is then applied to Viterbi detector **238** adapted to determine the binary bit pattern represented by the signal using a Viterbi algorithm. Parity decoder **240** then removes the parity bit from the determined bit pattern and RLL decoder **242** converts the result into a serial bit stream by applying a reverse run-length limited algorithm. The serial bit stream is then converted into a parallel stream (not shown) and output from read path **220** via interface **118**.

The analog signal applied to read path **220** is essentially a series of alternating positive and negative voltage pulses. In an ideal situation, pulses of different polarity would have identical

shapes/amplitudes, i.e. the shape of each pulse would be described by the time domain function

$P(t) = bh(t)$, where $h(t)$ is a function determining the pulse shape and $b = \pm 1$ is a coefficient determining the pulse polarity. However, in practice, non-linear effects affecting the response of MR heads cause the amplitudes of positive and negative pulses to differ and vary across the pulse sequence. As already mentioned, this pulse disparity/variation adversely affects the performance of disk drives. MRA circuit 226 is designed to deal with this problem by reducing said pulse disparity/variation and providing a signal having pulses of substantially uniform amplitudes across the pulse sequence.

Fig. 3 shows a block diagram of a prior-art MRA circuit 326 disclosed in U.S. Patent No. 6,633,447, the teachings of which are incorporated herein by reference, which circuit can be used as MRA circuit 226 in read/write channel 208. MRA circuit 326 is adapted to operate in conjunction with an MR head having substantially the following transfer function:

$$z(t) = x(t) + \alpha x(t)^2 \quad (1)$$

where $x(t)$ and $z(t)$ are the input and output signals, respectively, of the MR head at time t , and α is a coefficient. For relatively small values of α , the original non-distorted signal $x(t)$ can be recovered from the output signal $z(t)$ using the following second-order approximation:

$$y(t) = z(t) - \alpha z(t)^2 \quad (2)$$

where $y(t)$ represents an approximated value of $x(t)$.

MRA circuit 326 is a mixer circuit that implements Eq. (2) to balance pulse amplitudes and, therefore, improve the operation of the disk drive. In MRA circuit 326, signal $z(t)$ received from, e.g., VGA 224 (Fig. 2), is sent along two different signal paths labeled 302 and 304 in Fig. 3. Signal path 304 includes (I) a square-term generator 306 adapted to square the applied signal and (II) a linear multiplier 308 adapted to multiply the output of the square-term generator by a constant (a). In a preferred configuration $a = -\alpha$. A summation circuit 310 then adds the signals received via the two signal paths to generate balanced signal $y(t)$, in which the pulse imbalance induced by the MR head is reduced.

One problem with MRA circuit 326 is that it can correct signal asymmetry only within a relatively narrow asymmetry range. Range limitations are due to the fact that the second-order approximation given by Eq. (2) breaks down at relatively high signal asymmetry, i.e., at a relatively large value of α . The breakdown manifests itself, for example, by the fact that, at certain α , signal $y(t)$ produced in accordance with Eq. (2) acquires a different polarity than signal $z(t)$, which is an obviously incorrect result. The present invention deals with this problem by using a higher-order approximation than that of Eq. (2). More specifically, in addition to the second-order correction term, certain embodiments of the invention provide a third-order correction term and, optionally, other high-order correction terms, which is generalized by Eq. (3a) as follows:

$$y(t) = z(t) + b_2 z(t)^2 + b_3 z(t)^3 + O(z(t)^4) \quad (3a)$$

where $O(z(t)^4)$ represents a sum of the optional high-order terms starting with the fourth order, and b_2 and b_3 are constants. In a preferred embodiment, the following constant values are used:

$$b_2 = -\alpha \quad (3b)$$

$$b_3 = \frac{\alpha^2}{2} \quad (3c)$$

One skilled in the art will appreciate that the approximation given by Eqs. (3a-c) holds for a wider range of α values than the approximation of Eq. (2). As a result, MRA circuits of the invention that implement Eq. (3) can correct signal asymmetry within a relatively wide asymmetry range.

Fig. 4 shows a block diagram of an MRA circuit 426 that can be used as MRA circuit 226 in read/write channel 208 according to one embodiment of the present invention. MRA circuit 426 has two cascaded circuits 326a-b. More specifically, signal $z(t)$ applied to MRA circuit 426, e.g., by VGA 224 (Fig. 2), is applied to MRA circuit 326a, the output of which is then applied to MRA circuit 326b to generate balanced signal $y(t)$. Assuming that the multiplication constant (a) of each of linear multipliers 308a-b is $-c/2$, where c is a constant, the transfer function of MRA circuit 426 is given by Eq. (4) as follows:

$$y(t) = z(t) - cz(t)^2 + \frac{c^2}{2} z(t)^3 - \frac{c^3}{8} z(t)^4 \quad (4)$$

Comparing Eqs. (3) and (4), one finds that Eq. (4) is a species of Eq. (3), wherein $\alpha = c$ and $O(z(t)^4)$ is truncated at the fourth-order term.

Fig. 5 shows a block diagram of an MRA circuit 526 that can be used as MRA circuit 226 in read/write channel 208 according to another embodiment of the present invention. MRA circuit 526 is substantially a variable-gain amplifier. Signal $z(t)$ applied to MRA circuit 526, e.g., by VGA 224 (Fig. 2), is sent along two signal paths labeled 502 and 504 in Fig. 4. Signal path 504 has (I) a linear multiplier 508 that is similar to linear multiplier 308 (Fig. 3) and (II) an exponential-term generator 512 adapted to generate an output signal having an amplitude substantially equal to the exponent of the input signal. A multiplier circuit 514 multiplies the signals received via the two paths to generate balanced signal $y(t)$. Assuming that the multiplication constant of linear multiplier 508 is $-c$, the transfer function of MRA circuit 526 is given by Eq. (5) as follows:

$$y(t) = z(t) \exp(-cz(t)) = z(t) - cz(t)^2 + \frac{c^2}{2} z(t)^3 - \frac{c^3}{6} z(t)^4 + \dots \quad (5)$$

Similar to Eq. (4), Eq. (5) is a species of Eqs. (3a-c), wherein $\alpha = c$ and $O(z(t)^4)$ corresponds to the residual sum of a Taylor expansion series of the exponent.

Fig. 6 shows a block diagram of an MRA circuit 626 that can be used as MRA circuit 226 in read/write channel 208 according to yet another embodiment of the present invention. MRA circuit 626 is a differential variable-gain amplifier, which has two differential inputs, each input receiving a copy of input signal $z(t)$ of appropriate polarity, and two differential outputs, each output having a copy of output signal $y(t)$ of appropriate polarity. MRA circuit 626 includes a differential amplifier 602 in an inverting gain configuration whose gain is controlled by four MOS devices 604n, 604p, 606n, and 606p. Each MOS device 604 is an arrayed MOS transistor having a source (S), a drain (D), and a plurality of fingers (gates, G), each of which fingers controls a conducting channel between the source and the drain. Each MOS device 604 is connected to differential amplifier 602 such that its source-to-drain conductance provides an input resistance to the differential amplifier. More specifically, the source of each MOS device 604 receives, via the corresponding source follower 610a, input signal $z(t)$ of appropriate polarity while its drain is connected to the appropriate input of differential amplifier 602. Similarly, each MOS device 606 is an arrayed MOS transistor having a source (S), a drain (D), and a plurality of fingers (gates, G), each of which fingers controls a conducting channel between the source and the drain. Each MOS device 606 is connected to differential amplifier 602 such that its source-to-drain conductance provides a feedback resistance to the differential amplifier. The source of each MOS device 606 receives, via the corresponding source follower 610b, output signal $y(t)$ of appropriate polarity while its drain is connected to the drain of the corresponding MOS device 604 and to the corresponding input of differential amplifier 602.

The conductance between the source and the drain of each MOS device 604 and 606 is controlled by m (where, $m > 1$) fingers (gates), each of which can be biased independent of other fingers. Switch sets 614 and 616, each controlled by a multi-bit (e.g., n -bit, where $n > 1$) control signal 612, can couple each finger to the positive or negative input of MRA circuit 626. A representative circuit for generating control signal 612 is disclosed in U.S. Patent No. 6,587,292, the teachings of which are incorporated herein by reference. Briefly, the circuit for generating multi-bit control signal 612 estimates an asymmetry error in the signal generated by the MR head coupled to MRA circuit 626 (e.g., read/write head 104 of Fig. 1), which provides an estimate for the value of α (see Eq. (1)). Multi-bit control signal 612 is generated based on this estimate and applied to switch sets 614 and 616 to connect the gates of MOS devices 604 and 606, respectively, to input signal $\pm z(t)$ to appropriately scale the influence of the input signal on the source-to-drain conductance of those MOS devices.

Each of switch sets **614** and **616** has m switches, each switch having two input ports and one output port. Each switch in switch set **614** is coupled to one finger in MOS device **604p** and one finger in MOS device **604n**. Similarly, each switch in switch set **616** is coupled to one finger in MOS device **606p** and one finger in MOS device **606n**. Based on multi-bit control signal **612**, each switch couples a selected input port to the output port. As a result, the gates of MOS devices **604** and **606** are coupled to input signal $z(t)$ of selected polarity and the conductance of those MOS devices becomes modulated with the input signal. In addition, finger connections provided by switch sets **614** and **616** are such that the conductance of MOS devices **604** and the conductance of MOS devices **606** change in a manner complementary to each other. More specifically, the conductance, σ , of each of MOS devices **604** and **606** is varied in accordance with Eqs. (6a) and (6b) as follows:

$$\sigma_{604} = \sigma_i \left(1 - \frac{c}{2} z(t)\right) \quad (6a)$$

$$\sigma_{606} = \sigma_f \left(1 + \frac{c}{2} z(t)\right) \quad (6b)$$

where c is a scaling factor corresponding to control signal **612**, and σ_i and σ_f are constants. Therefore, when the conductance of MOS device **604** increases, the conductance of MOS device **606** decreases by a proportionate amount, and vice versa.

The gain, G , of differential amplifier **602** is determined by the input and feedback resistances, R_{input} and $R_{feedback}$, provided by MOS devices **604** and **606**, respectively. Using Eqs. (6a) and (6b) and the inverse relationship between resistance and conductance, one obtains the following expression for G :

$$G = \frac{R_{feedback}}{R_{input}} = g_0 \frac{1 - \frac{c}{2} z(t)}{1 + \frac{c}{2} z(t)} \quad (7)$$

where $g_0 = \sigma_i / \sigma_f$. In a representative implementation of MRA circuit **626**, MOS devices **604** and **606** are designed such that the value of g_0 is approximately 1. However, it may be preferable to have σ_i slightly larger than σ_f to compensate for gain losses elsewhere in the signal path. Assuming $g_0 = 1$ and using the definition of G as $y(t)/z(t)$, one arrives at the following transfer function for MRA circuit **626**:

$$y(t) = z(t) \frac{1 - \frac{c}{2} z(t)}{1 + \frac{c}{2} z(t)} = z(t) - cz(t)^2 + \frac{c^2}{2} z(t)^3 - \frac{c^3}{4} z(t)^4 + \dots \quad (8)$$

Similar to Eq. (4), Eq. (8) is a species of Eq. (3), wherein $\alpha = c$ and $O(z(t)^4)$ corresponds to the residual sum of a Taylor expansion series of the denominator multiplied by the numerator.

Fig. 7 shows a diagram of a circuit **700** that can be used in MRA circuit **626** according to one embodiment of the present invention. More specifically, circuit **700** has four MOS devices M0, M1, M7, and M8 that can be used as MOS devices **604p**, **604n**, **606n**, and **606p**, respectively, in MRA circuit **626**. In circuit **700**, MOS devices M0, M1, M7, and M8 are coupled to a differential amplifier **702** that is analogous to differential amplifier **602** of Fig 6. Each of MOS devices M0, M1, M7, and M8 is a MOS transistor having sixteen fingers (gates). Each finger is connected to a corresponding line in one of the buses labeled gn<15:0> and gp<15:0>, where the former controls the fingers of MOS devices M7 and M8 and the latter controls the fingers of MOS devices M0 and M1. Buses gn<15:0> and gp<15:0> connect MOS devices M0, M1, M7, and M8 to switch sets analogous to switch sets **614** and **616** of Fig. 6. Signals labeled sat_ctl and v18a provide appropriate bias voltages to each of MOS devices M0, M1, M7, and M8, and signals labeled fol_p and fol_n represent buffered, level-shifted versions of the input signal that are generated, e.g., by source followers **610a** in Fig. 6.

In one embodiment, each of MOS devices M0, M1, M7, and M8 is implemented as a device analogous to sixteen NMOS transistors having a common source, a common drain, and sixteen separate gate nodes. Due to the source/drain sharing between adjacent transistors, this embodiment takes up a relatively small chip area. A preferred layout style is similar to an inter-digitated (double-comb) layout style typically used to implement a single large NMOS transistor having a gate width/length ratio of about 1000, in which the source and the drain appear as alternating stripes separated by the gate areas. However, one difference between these two layouts is that, in the present invention, the gate areas are not connected together to form a single node, but rather, represent sixteen separate gates of sixteen transistors. Using device M0 as an example, the first stripe is the drain M0<0>; the second stripe is the source of M0<0> and simultaneously the source of M0<1>; the third stripe is the drain of M0<1> and simultaneously the drain of M0<2>, and so forth; and the last stripe is the drain of M0<15>. The gate of each transistor is located between the stripes serving as the source and drain of that transistor.

Figs. 8A-B show diagrams of circuits **810** and **820** that can be used in switch sets **614** and **616** according to one embodiment of the present invention. More specifically, Figs. 8A-B illustrate switch sets adapted for use in conjunction with circuit **700** of Fig. 7 to connect the differential input signal to buses gn<15:0> and gp<15:0>. Circuit **810** is adapted to connect the differential input signal to lines gn<0> and gp<0> of buses gn<15:0> and gp<15:0>, respectively, and, as such, can control one finger in each of MOS devices M0, M1, M7, and M8 of circuit **700**. Circuit **820** is adapted to connect the input signal to lines gn<1> to gn<15> and gp<1> to gp<15> of buses gn<15:0> and gp<15:0>, respectively, and, as such, can control the remaining fifteen fingers in each of MOS devices M0, M1, M7, and M8 of circuit **700**.

Referring to Fig. 8A, circuit **810** has a resistor divider R2<7:0> and two transistor sets M52<7:0> and M53<7:0>. Resistor divider R2<7:0> has two end terminals and seven intermediate terminals, which

provides eight different resistor values, preferably in equal increments. Each of the end terminals receives the input signal of appropriate polarity via line vga_n or vga_p , while each of the intermediate terminals is connected to a corresponding line of a bus $res_str<7:1>$. Each of transistor sets $M52<7:0>$ and $M53<7:0>$ has eight transistors that are connected together at their drains. The drains in transistor set $M52<7:0>$ are also connected to line $gn<0>$ of bus $gn<15:0>$, and the drains in transistor set $M53<7:0>$ are similarly connected to line $gp<0>$ of bus $gp<15:0>$. The source of each transistor in transistor set $M52<7:0>$ is coupled to resistor divider $R2<7:0>$ via one of the lines in vga_n and $res_str<7:1>$, and the source of each transistor in transistor set $M53<7:0>$ is similarly coupled to the resistor divider via one of the lines in vga_p and $res_str<7:1>$.

Each transistor in transistor sets $M52<7:0>$ and $M53<7:0>$ can be switched between the “on” and “off” states using a corresponding line of bus $frac_mr<7:0>$ connected to the gate of that transistor. Signals applied to bus $frac_mr<7:0>$ are generated, e.g., based on the three least significant digits of multi-bit control signal **612** (see Fig. 6) and are such that, at any given time, only one of those signals is active low. As a result, only one transistor in each transistor set is in the “on” state, which connects lines $gn<0>$ and $gp<0>$ to the corresponding terminals of resistor divider $R2<7:0>$. Since both transistor sets are controlled by bus $frac_mr<7:0>$, they provide complementary fractional switching of lines $gn<0>$ and $gp<0>$ between the levels corresponding to the negative and positive input signals. One skilled in the art will appreciate that this fractional switching can be used, for example, to provide fine adjustment to the value of the scaling factor that determines conductance changes in MOS devices **604** and **606** of MRA circuit **626** (see Eqs. (6a-b) and Fig. 6).

Referring to Fig. 8B, circuit **820** has four transistor sets $M55<15:1>$, $M56<15:1>$, $M65<15:1>$, and $M66<15:1>$, each having fifteen transistors. Transistors in transistor sets $M55<15:1>$ and $M56<15:1>$ are connected together at their sources, which are also connected to the positive input signal. Similarly, transistors in transistor sets $M65<15:1>$ and $M66<15:1>$ are connected together at their drains, which are also connected to the negative input signal. The drain of each transistor in transistor set $M55<15:1>$ is connected to the source of a corresponding transistor in transistor set $M66<15:1>$ and to the corresponding line in bus $gp<15:1>$. Similarly, the drain of each transistor in transistor set $M56<15:1>$ is connected to the source of a corresponding transistor in transistor set $M65<15:1>$ and to the corresponding line in bus $gn<15:1>$.

Each transistor in transistor sets $M55<15:1>$, $M56<15:1>$, $M65<15:1>$, and $M66<15:1>$ can be switched between the “on” and “off” states using a corresponding line in buses $therm_n<15:1>$ and $therm_p<15:1>$ that is connected to the gate of that transistor. The signals applied to buses $therm_n<15:1>$ and $therm_p<15:1>$ can be generated, e.g., based on multi-bit control signal **612** (see Fig. 6) and are complementary to each other. More specifically, at any given time, only one of the two

transistors connected to any line $gn_{<k>}$ of bus $gn_{<15:1>}$ or any line $gp_{<k>}$ of bus $gp_{<15:1>}$, where $1 \leq k \leq 15$, is in the “on” state, thereby connecting that line to the input signal of the corresponding polarity. In addition, when any given line $gn_{<k>}$ of bus $gn_{<15:1>}$ is connected to the positive input signal, the corresponding line $gp_{<k>}$ of bus $gp_{<15:1>}$ is connected to the negative input signal, and vice versa. One skilled in the art will appreciate that the complementary switching implemented in circuit 820 can be used, for example, to provide complementary conductance changes in MOS devices 604 and 606 of MRA circuit 626 (and Fig. 6).

While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Although the present invention has been described in the context of CMOS technology, it will be understood that the present invention can be implemented using other technologies, such as nMOS, pMOS, or other non-MOS technologies. The substrates used in the circuits of the present invention may be made of any suitable semiconductor material, such as Si, GaAs, or InP, with different dopant types to form various structures. Although circuits of the present invention have been described as adapted to reduce signal asymmetry, one skilled in the art will appreciate that these circuits may also be adapted to change (i.e., increase or reduce) said signal asymmetry. Circuits of the invention may be used in conjunction with MR heads having a transfer function different from that given by Eq. (1). In general, circuits of the invention provide a signal contribution corresponding to an order of the input signal higher than the second order, which contribution may or may not include a third-order term. Various modifications of the described embodiments, as well as other embodiments of the invention, which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

Although the steps in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those steps, those steps are not necessarily intended to be limited to being implemented in that particular sequence.